# TWO-WAY TIME TRANSFER WITH DUAL PSEUDO-RANDOM NOISE CODES

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**Abstract**

***We have developed a new Two-Way Satellite Time and Frequency Transfer modem in order to improve measurement precision and reduce operational costs. The new modem is based on software-defined radio technology. Transmission and reception of signals between distinct ground stations are based on a pseudo-random noise code similar to the one used for GALILEO or GPS's modernized ranging signal. Our developed signal is introduced by a pair of pseudo-random noise codes that are separated in the frequency domain. The advantage of this signal is that the operational costs are below those of conventional signals, but yield better precision.***

***We have recently carried out Two-Way Time Transfer experiment using the new signal. For evaluation of time transfer precision, GPS observations have been taken at the same time. Results show that the measurement precision of the new signal is better than 100 ps, and clock behavior of two stations was found to be consistent compared with GPS carrier-phase time transfer.***

## INTRODUCTION

Two-Way Satellite Time and Frequency Transfer **[1]** (henceforth, Two-Way) using geostationary communication satellites is one of the leading technologies for determination of International Atomic Time (TAI). The measurement precision of Two-Way is limited by the chip rate of the pseudo-random noise (PRN) code which is used as timing signal. The conventional Two-Way method uses 2 to 2.5 Mcps PRN codes, and achieves a measurement precision of 1 ns or better. Since an increase of chip rate requires an enlargement of the bandwidth of the satellite transponder, the usage of broadband PRN codes for more precise time transfer links leads to an increase of connection fees of commercial communication satellites.

The binary offset carrier (BOC) adopted by GALILEO or the modernized GPS ranging signal **[2]** brings up an idea to overcome this problem. Though BOC signal does not directly solve our problem, a pair of narrow-band PRN codes separated in frequency space is capable of decreasing the occupied bandwidth, yielding higher measurement precision **[3]**. The National Institute of Information and Communication Technology (NICT) has developed a new Two-Way Time Transfer modem using dual pseudo-random noise (DPN) codes. The modem is based on software-defined radio technology, and is composed of a

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| 1. REPORT DATE | 2. REPORT TYPE | 3. DATES COVERED |
|---|---|---|
| **01 DEC 2008** | **N/A** | **-** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Two-Way Time Transfer With Dual Pseudo-Random Noise Codes** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**National Institute of Information and Communications Technology 4-2-1, Nukui-Kita, Koganei, Tokyo 184-8795, Japan** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**See also ADM002186. Annual Precise Time and Time Interval Systems and Applications Meeting (40th) Held in Reston, Virginia on 1-4 December 2008, The original document contains color images.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **UU** | **8** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

versatile analog-to-digital sampler, a waveform generator, as well as a personal computer. Since the main part of digital signal processing is performed by software on the personal computer, the system is inexpensive and flexible. The drawback of such a system is that is has a slow processing speed, which has not allowed us to process Two-Way Time Transfer in real time yet.

Currently, we are testing the performance of the developed system. We have equipped two ground stations with this new modem, and in the first step, a common clock test has been carried out. The results of this test have been presented at ATF 2008 **[4]**. We are currently working on the second step, i.e. a short-baseline test. A first short-baseline time transfer experiment will be described in the following, and the results of a comparison with GPS carrier-phase time transfer will be presented.

## PRINCIPLE OF DUAL PSEUDO-RANDOM NOISE CODES

A BOC signal is generated by the addition of square-wave modulation using the normal PRN code. The generated BOC signal is spread in frequency domain depending on the frequency of square wave, which is called sub-carrier. The concept of DPN signal is the same to that of BOC signal, whereas the sub-carrier of DPN signal is using a sine wave instead of a square wave, and all side-bands of the generated signal are filtered out. Figure 1 shows the power spectral density of BOC and DPN. The center frequency is 10 MHz, and the sub-carrier and chip frequency are 2.5575 MHz and 1.023 MHz, respectively.

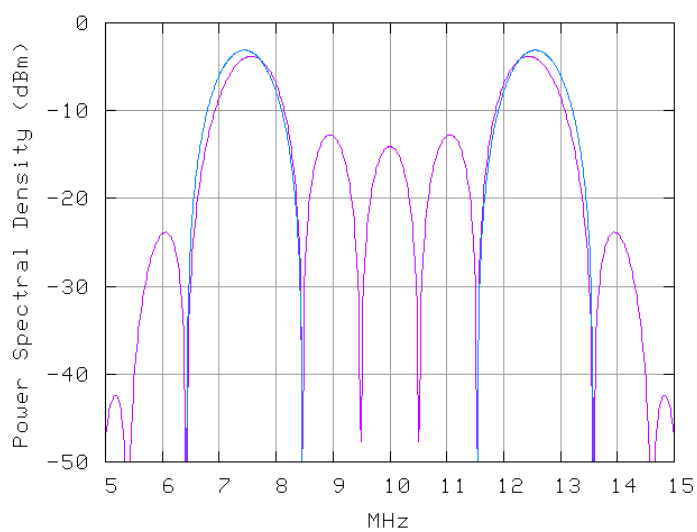


Figure 1. Power spectral density of BOC (purple line) and DPN (blue line).

The occupied bandwidth of the DPN signal is obtained by the summation of two PRNs. Since group delays of DPN signal are derived from the slope of cross-correlation spectral phase, the observation error of the DPN signal can be estimated by Eqn. (1), which depends on the sub-carrier frequency and not on the chip rate of each PRN.

$$\sigma_\tau \approx \frac{1}{4\pi f_s \sqrt{T\, C/N_0}} \quad (1)$$

The sub-carrier frequency is denoted by $f_s$, $T$ is the integration time, and $C/N_0$ is the carrier-to-noise ratio. Thus, the measurement precision of the DPN signal has a C/No of 50 dBHz with a 200 kcps code and a 10-MHz sub-carrier is 25 ps at an averaging time of 1 s. This precision is about 20 times better than those of conventional Two-Way signals, which provide about 500 ps under the same conditions. Thus, usage of a DPN signal at low chip rates and with a high frequency of sub-carrier leads to a significant improvement of measurement precision, accompanied by a reduction of operational cost.

## SYSTEM DESIGN OF THE NEW MODEM

The DPN modem consists of an A/D sampler and a waveform generator. The specifications of the equipment are listed in Table 1 and Table 2, respectively. The design concept of the DPN modem aims to be inexpensive and flexible. Most signal processing parts are realized by software implementations on the host computer. The waveform generator generates an arbitrary signal using a 204.6-MHz sampling clock. This generated signal is set on the memory by host computer. Because the size of the waveform in memory is 1 MB, the maximum length per period of arbitrary signal has to be less than 5 ms. To satisfy this condition, we have selected a 511-bit sequence using a 127.75-kHz chip rate for the DPN signal. The sub-carrier frequency is 10.24 MHz, which meets the bandwidth requirements of the satellite transponder. The received signal from the other stations is converted to digital signal by A/D sampler with a 64-MHz sampling clock. We have been using the versatile A/D sampler, which has been originally developed for VLBI observations **[5]**, since this sampler can digitize the input signal using synchronization impulses from an external reference source. Because most parts of the frequency components of the received signal are noise, the A/D sampler decimates the signal with a configurable filter before sending it to the host computer.

The software of the host computer correlates between the received signal and the replica code in order to determine the group delay and cross-spectral phase at the center frequency of each PRN. Consequently, precise group delay is obtained by using the slope of the cross-spectral phase over a separation of 20.24 MHz. Since the group delay determined from the cross-spectral phase has an ambiguity spacing of about 24.5 ns (half of the 20.24-MHz period), the coarse group delay of each PRN is used to solve for this ambiguity.

Table 1, Specification of K5/VSSP A/D sampler.

| | |
|---|---|
| Sampling frequency | 40 kHz to 64 MHz, 11 modes |
| A/D bit | 1, 2, 4, 8 bit |
| Number of channels | 4 |
| Reference signal | 5 or 10 MHz & 1 PPS |
| Configurable filter | Max. 64 taps |
| Interface | USB 2.0 |

Table 2, Specification of waveform generator.

| | |
|---|---|
| Sampling frequency | 204.6 MHz |
| D/A bit | 8 bit |
| Number of channels | 2 |
| Reference signal | 10 MHz & 1 PPS |
| Waveform memory | 512 KB x 2 / CH |
| Overlay data memory | 64 KB / CH |
| Interface | USB 2.0 |

## FIRST TWO-WAY EXPERIMENT USING DPN SIGNAL

We carried out the first Two-Way Time Transfer experiment using the newly developed DPN signal. Two ground stations were located on a 500-m north-south baseline situated inside the headquarters of NICT in Tokyo, Japan. One station was located on top of the building which houses the time and frequency section, and UTC (NICT) was used as reference signal. The second station was located at Keystone VLBI station, and the reference signal was obtained from a free-running H.M. All equipment of the two stations except the Two-Way modem was identical to existing conventional Two-Way systems. Additionally, a dual frequency GPS receiver was also available at both stations. Whereas, the GPS receiver near the VLBI station was a Trimble NetRS, and the other station was equipped with an ASHTECH Z-XII Metronome. Both receivers were connected to the reference signals of each Two-Way system. Figure 2 shows the picture of ground station located next to the VLBI building.

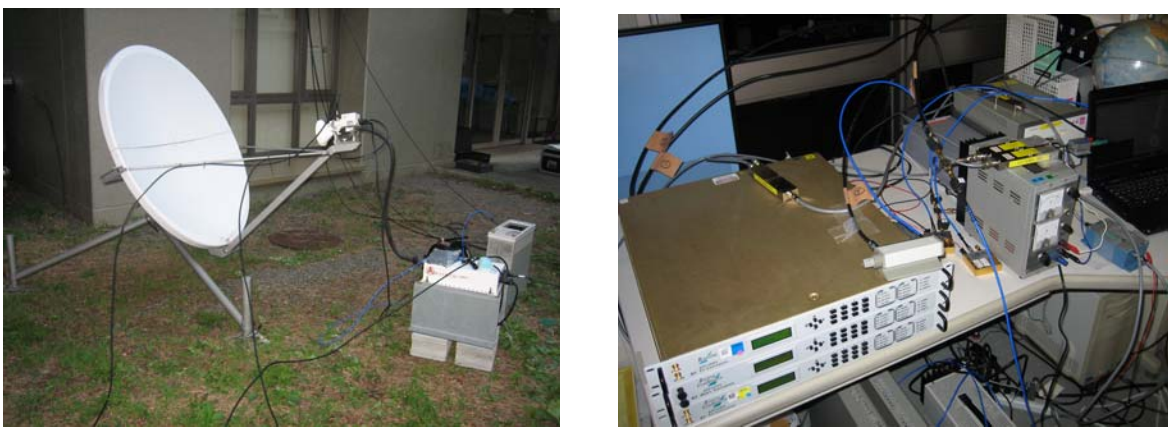

Figure 2. Ground station located at near the Keystone VLBI site. The left picture shows outdoor 1.2-m antenna, and the right picture displays the indoor experiment equipment.

Since our system has not allowed real-time processing until now, we performed this experiment by postprocessing. The sampling observations of both stations were stored on a hard disk on the host computer, and cross-correlation processing was carried out after the end of the experiment. Due to limitation of hard disk capacity, only 30-second samplings were observed every 10 minutes. Using this setup, we performed a 24-hour Two-Way Time Tansfer experiment on 15 October 2008.

Figure 3 shows the time difference between UTC (NICT) and VLBI H.M. Blue crosses show the time differences computed by Two-Way Time Transfer, and green crosses show those of GPS carrier phase time transfer. Each data point of Two-Way result represents the simple averaged value from 30 seconds of time difference data. On the other hand, GPS results were computed by precise point positioning using a parameter interval length of 5 minutes.

Some jumps with a magnitude of hundred picoseconds to a few nanoseconds can be seen only in the Two-Way results. This needs further investigation. We calculated the first-order component of GPS carrier-phase time transfer, and removed the linear trend from both time transfer results (lower plot in Figure 3). Although the measurement precision of both methods is similar, the time difference is slightly inconsistent within a few hundred picoseconds. Up to now, it is not clear which system, Two-Way or GPS, introduces this inconsistency.

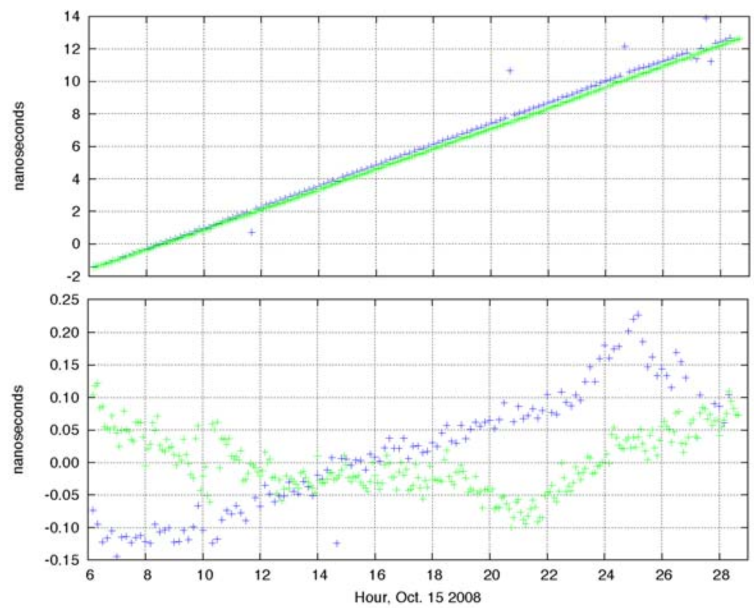


Figure 3. Time difference between UTC (NICT) and VLBI H.M. Blue crosses relate to Two-Way, and green crosses show the GPS PPP results. The upper plot shows the actual time difference, and the lower plot shows the time difference after linear trend, computed from GPS PPP results, has been removed.

In the final step, we computed the time transfer stability of both methods. Beforehand, the time jumps of Two-Way result were removed (Figure 4). As a result, it can be stated that time transfer stability until 1,000 seconds is almost identical when comparing the Two-Way and GPS carrier phase. However, a different behavior for averaging times of 5,000 seconds is found. The stabilities of Two-Way and GPS carrier phase at an averaging time of 10 minute is $5.2 \times 10^{-14}$ and $5.5 \times 10^{-14}$ respectively.

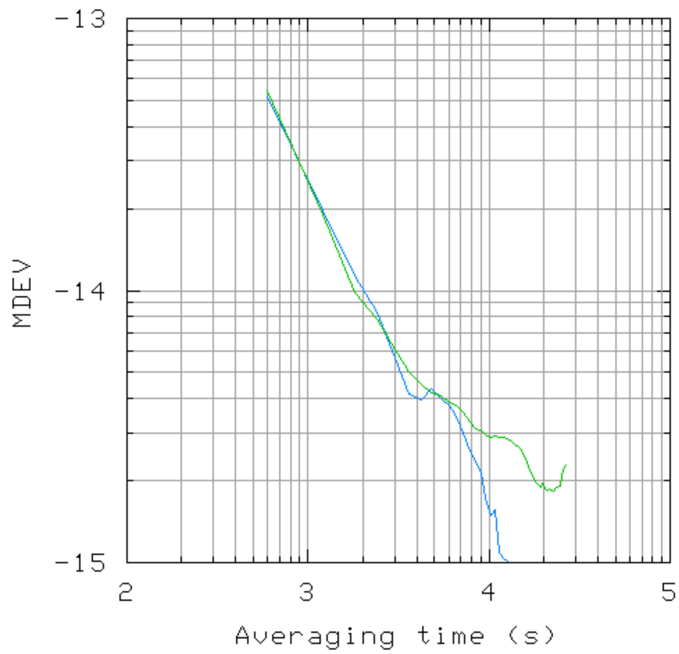


Figure 4. Time transfer stability of Two-Way and GPS PPP. The X and Y labels show power to base 10. The blue line shows the stability of Two-Way, and green line shows the corresponding performance of GPS PPP.

## CONCLUSION

We investigated a precise timing signal for Two-Way Satellite Time and Frequency Transfer, and demonstrated its measurement precision in this paper. The time transfer precision with a DPN signal is equivalent to that of the GPS carrier-phase method for averaging time less than an hour. However, clock behavior on the long term was slightly different between both methods. Since the time span of this experiment was only 24 hours, further long-term observations are required for a rigorous estimation of the measurement precision.

We also demonstrated, the performance of our software is based Two-Way Time Transfer modem. Some time jumps were found in Two-Way Time Transfer result, which were not present with GPS carrier-phase time transfer. The reason of these jumps is currently under investigation. Real-time processing with our software modem has not been achieved yet. Thus, we are planning to implement the algorithms on a parallel platform using a graphics processing unit **[6]** to realize real-time time and frequency transfer.

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